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ECOLE POLYTECHNIQUE
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

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October 2013(revised version 2013-08)

Cahier n° 2013-27

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Capacity decisions with demand fluctuations and carbon leakage. *

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October 2013

Abstract

For carbon-intensive, internationally-traded industrial goods, a unilateral increase in the domestic CO_2 price may result in the reduction of the domestic production but an increase of imports. In such sectors as electricity, cement or steel, the trade flows result more from short-term regional disequilibria between supply and demand than from international competition. This paper formalizes this empirical observation and characterizes its impact on leakage. Domestic firms invest in home plants under uncertainty; then, as uncertainty unfolds, they may source the home market from their home plants or from imports. We prove that there would be no leakage in the short-term (without capacity adaptation) but there would be in the long-term (with capacity adaption). Furthermore, the larger the uncertainty the larger the leakage is. We also characterize the impacts of uncertainty on the (short-term and long-term) pass-through rates. In the concluding section we discuss the implications of these results for the evaluation of climate policies.

JEL Classification: D81, D92, Q56, L13.
Keywords: carbon leakage, demand fluctuations, capacity decisions.

*Financial support from the Business Economics and the Sustainable Development Chairs at Ecole Polytechnique is gratefully acknowledged.

1 Introduction

When a country A implements a unilateral climate policy carbon leakage refers to the fact that the reduction of emissions in country A may be partly offset by the increase of emissions in the rest of the world.

The literature on carbon leakage has been initiated by Rutherford (1992) and Felder and Rutherford (1993) who coined the term "leakage". Several channels through which leakage could arise have been identified. This paper focuses on the *terms-of-trade* channel, also related to the competitiveness issue: the increase of production cost due to the climate policy may induce a relocation of production in *trade-exposed and energy intensive* sectors.[1] The empirical importance of this issue has generated a large number of models which evaluate the ex-ante consequences of unilateral climate policies and the relative merits of remedies (Droege and Cooper, 2009).

In some trade-exposed and energy intensive sectors the trade flows result more from short-term regional disequilibria between supply and demand than from international competition. For instance the short term capacity constraints observed in Europe around 2005-2007 explain better the trade patterns for cement and steel than the pressure of international competition between the EU and non EU countries (Hourcade et al., 2008). The objective of the present article is to explicitly model this particular mechanism of trade and analyze leakage in that context.

Let us consider a set of regional markets for a homogeneous good for which transportation costs are high and capacity constraints matter. In each regional market the demand is uncertain and capacities can only be adjusted in the long term. The supply in each market is made by a limited number of home firms. Each firm has access to two sources: either from its own plants located in the region or imports that it can buy on a cross regional market directly operated by all the firms of the sector. In the short term home production is less costly than importing, so that imports only occur when home capacities are saturated. We assume that the price of cross regional exchanges is independent of the demand and supply conditions in any given region: imports and exports in any given region are relatively small compared to the world market, and demand variations are local and not correlated. We are interested in modeling the capacity decisions of the oligopoly in that region. For simplicity we assume that no profit is expected from eventual exports.

We distinguish between short term and long term effects. Suppose home unilaterally adopts a more stringent climate policy (i.e. increases the price for CO_2 emissions); in the short term the capacities are given, in the long term the capacities are adapted to the change in the CO_2 price. Since imports are driven by the capacity constraints, in the short term, these constraints are not

[1] Trade-exposed and energy intensive sectors are also denominated as "sensitive" sectors. A sector is "sensitive" under two conditions: (Grubb and Neuhoff, 2006) the impact of the CO_2 price is high relative to its value added (*value at stake*), it is highly exposed to international trade (*import intensity*). If both conditions are satisfied sectoral leakage is high. Typical sensitive sectors are: cement, steel, basic chemicals, aluminum...

affected by the change in the CO_2 price, the short term leakage rate is null. We show that in the long term the reduction of capacity is amplified by uncertainty relative to a situation without uncertainty; this amplification induces a long term leakage rate which increases with the level of uncertainty. It is precisely the introduction of uncertainty and its feed back on capacity decisions that generate long term leakage, while there would not be any without uncertainty. We also show that the short term pass through rate is lower than the long term one.

The rest of the paper is organized as follows. The relation with the literature is reviewed in Section 2. The model is described in Section 3 and analyzed in Section 4. The concluding section discusses possible extensions of the model. Policy implications of our results are also discussed.

2 Related literature

There is a consequent literature on carbon leakage.[2] The two most scrutinized channels for leakage are: the energy-market and the terms-of-trade channels. The energy-market channel refers to the possible increased consumption of energy intensive goods in unregulated countries due to the lower world price of fossil fuels induced by the lower consumption of these goods coming from regulated countries. The terms-of-trade channel refers to the increased imports of energy intensive goods in regulated countries from unregulated ones.[3]

Ordinarily the energy-driven channel generates a larger fraction of the total leakage than the terms-of-trade channel.[4] But competitiveness issues are an important political issue. This explains their disproportionate role in the design of emission trading schemes (see Hood, 2010, for a review of how existing or forthcoming schemes in Australia, California, Europe, New Zealand... are influenced by competitiveness issues).

Two main approaches have been commonly used to quantify the terms-of-trade channel. One approach consists in assuming that home and foreign products are imperfect substitutes (e.g. Fischer and Fox, 2012); the other one is built on imperfect competition *à la* Cournot (e.g. Babiker, 2005; Ponssard and Walker, 2008; Meunier and Ponssard, 2012) or monopolistic competition

[2]The bulk of the literature consist in numerical simulations of policies with multi-countries multi-sectors general equilibrium models. The supplement 2 of Energy Economics vol 34 on border carbon adjustment edited by Böhringer et al . (2012) is a good illustration of this literature.

[3]Several other channels have been identified: the diffusion of new green technologies can induce a negative leakage (Golombek and Hoel, 2004; Di Maria and Van der Werf, 2008; Gerlagh and Kuik, 2007), subsequent changes of wealth can induce a positive or negative leakage (Elliott and Fullerton, 2013), and the change of the marginal environmental damage modifies the optimal emissions in other countries (see for instance the work on environmental coalitions by Carraro and Siniscalco, 1993; Barrett, 1994).

[4]For example, Kuik (2001) examined a scenario in which only the EU implements its goal to reduce emission in the EU-ETS and found that only 1/10th of the global leakage can be attributed to the terms-of-trade channel. This is primarily due to the low production share of EU energy-intensive sectors relative to GDP.

(e.g. Balistreri and Rutherford, 2012).[5] The underlying explanation for intra-industry trade in these approaches is in line with the main body of the literature on international trade. Usually, intra-industry trade is explained by imperfect substitutability between home and foreign production, economies of scale and imperfect competition (Krugman, 1979, 1980; Brander, 1981).

We introduce a different rationale for intra-industry trade. We do consider a homogeneous product and Cournot competition but the international trade is due to regional capacity constraints. The motivation for our framework comes from the empirical literature. For instance Demailly and Quirion (2008) and the Cement Sustainability Initiative report (WBCSD, 2009) elaborate multi-regional models of the world cement industry over a 30 year time horizon. Regional supply and demand conditions determine regional capacities and international trade flows come from the imbalances caused by this myopic optimization. Ryan (2012) also introduces capacity constraints in his empirical analysis of the US cement industry. Fowlie et al. (2012) extends this empirical analysis to allow for imports and investigate the impacts of various unilateral climate policies in the US. The electricity sector provides another empirical context in which our framework may be relevant. Regional demand for electricity fluctuates. Cross regional flows come in part from regional imbalances between supply and demand. Bushnell and Chen (2012) discuss leakage for the Californian electricity sector under demand fluctuations and capacity constraints. While these empirical studies recognize capacity constraints, they do not analyze the role of uncertainty in the capacity decisions.

In Hourcade et al. (2008) (see chapter 3 entitled Deep-dive study: the EU cement and steel sectors) the authors investigate the reasons for the recent peak of imports observed in Europe in 2007. International price comparisons exhibit a low correlation coefficient suggesting loosely connected regional markets at the world level. Their explanation for trade relies on the regional disequilibria between supply and demand. For cement, they show that non EU imports clearly responded to capacity constraints. Quite surprisingly, in the same chapter section 3.2.4, the authors propose a model of carbon leakage based on perfect competition and imperfect substitutes, along the lines of Fischer and Fox (2012).

The role of uncertainty on leakage through its impact on capacity decisions remains to be formalized. Our goal is to fill the gap. We want to identify and explore the consequences of a unilateral change in a climate policy in a simple analytic model which allows the distinction between short term (without capacity adaptation) versus long term (with capacity adaptation) effects.

It is worth noting that the question of the relationship between capacity choice to demand uncertainty is a recurrent topic in the economic literature since the work of Rothshild and Stiglitz (1970, 1971). The interested reader is referred to Meunier et al. (2013) for a discussion of this aspect of our model

[5] The order of magnitude obtained for leakage in these models depends on the sectors under study and on modeling assumptions; i.e. 14% for steel and mineral products in Fischer and Fox (2012), 50% in Demailly and Quirion (2008) and 70% in Ponssard and Walker (2008) for cement, up to more than 100% in Babiker (2005) because of the relocation of energy intensive producers.

and its relationship to this literature. In Meunier et al. (2013) conditions under which capacity is either increasing or decreasing with respect to the range of uncertainty are derived in a more general model and the conclusions are empirically validated in the context of the US cement industry.

3 The model

The model features an oligopolistic market in which firms have to invest in capacity at home based on an uncertain future home demand. Then, the demand is known and firms can possibly imports in situation of capacity shortages. The good is homogeneous and imports only occur because of the combination of irreversibly of capacity decisions and demand uncertainty. Under certainty it would always be preferable to deliver to the home market via home location rather than via imports. The analysis is carried on assuming linearity in the long run average cost function (investment and production) and in the demand function. Import costs are also assumed to be linear. The demand function includes an additive random parameter uniformly distributed over a given range, the larger the range, the larger the demand variability. We assume a constant CO_2 emission factor for home and foreign production. The model is kept simple for analytical tractability. Extensions are discussed in the concluding section.

3.1 Assumptions

The total quantity produced is denoted q. The inverse demand function is assumed to be linear and random : $p(q,\theta) = a+\lambda\theta-bq$, in which a and b are two positive parameters. Uncertainty is introduced through two parameters: λ and θ. The parameter λ (in € per unit) measures the range of demand variations, the case of no uncertainty corresponds to $\lambda = 0$. The dimensionless random variable θ is assumed to be uniformly distributed on the interval: $[-1,+1]$ with density $1/2$. The parameter λ or the ratio λ/a (dimensionless) will indifferently be referred to as demand *variability*.

The good is produced by an oligopoly consisting of n identical firms. Each firm has access to two technologies: a *home technology* which refers to its home plants and a *foreign technology* which refers to its importing capabilities. To produce with the home technology the firm should first invest in capacity. In the short-term the firm cannot produce more than its capacity at home but it can import.

The (annualized) cost of a unit of capacity is c_k (in €/unit). With a unit of capacity the firm can produce at most one unit of the good for a variable cost c_h (in €/unit). The variable cost includes the impact of the CO_2 regulation. The cost function for the foreign technology involves a linear production cost and no investment cost. The marginal cost of imports is fixed and denoted c_f (in €/unit). It may be interpreted as an average delivered cost to the home market, i.e. the price of cross regional exchanges plus the transportation cost.

Three assumptions are made on the parameters values. In case of no uncertainty the home technology would be preferred to the foreign one, $c_k + c_h < c_f$, and the demand would be high enough to make production worthwhile, $a > c_h + c_k$. Furthermore, the range of demand variations is limited so that in all demand states, in the short term, it is worth producing with the home technology: $0 \leq \lambda \leq a - c_h$.

The decision process takes place in two steps. First, each firm decides its home capacity. Second, for each value of θ each firm chooses its home production and its imports (capacities are fixed). Firms compete in quantities, *à la* Cournot. Total capacity is denoted k, total home production is denoted q_h and imports q_f. To alleviate notations we do not index firms individual production and capacity. We want to study the influence of the demand variability λ and the CO_2 price through the variable cost c_h on the equilibrium total capacity to be denoted $k_n^*(\lambda, c_h)$ or simply k_n^*.

3.2 Equilibrium investments

We consider open-loop Nash equilibrium; when firms invest they do not take into account the strategic effects of their investment on the production of their rivals. These strategic effects would obscure the core mechanism at stake.

Lemma 1 *If demand variability is sufficiently large, the equilibrium capacity of an oligopoly of n firms is:*

$$k_n^* = \frac{n}{n+1}\frac{1}{b}\left[a - \frac{c_h + c_f}{2} + \lambda\left(1 - 2\frac{c_k}{c_f - c_h}\right)\right]. \tag{1}$$

The equilibrium home production and imports are:

	$-1 \leq \theta \leq \theta^-$	$\theta^- \leq \theta \leq \theta^+$	$\theta^+ \leq \theta \leq 1$
q_h	$\frac{n}{n+1}\frac{a-c_h}{b}$	k_n^*	k_n^*
q_f	0	0	$\frac{n}{n+1}\frac{a-c_f}{b} - k_n^*$

in which θ^- and θ^+ are:

$$\theta^- = 1 - \frac{c_k}{c_f - c_h} - \frac{c_f - c_h}{2\lambda} \text{ and } \theta^+ = 1 - \frac{c_k}{c_f - c_h} + \frac{c_f - c_h}{2\lambda} \tag{2}$$

The proof is in B.

We give the intuition for the result, using the case of a monopoly for ease of exposition. The monopoly long term profit $\pi(k)$ for a given capacity choice k is given by:

$$\pi(k) = \int_{-1}^{+1} \max_{(q_h \leq k, q_f \geq 0)} \left[pq - c_h q_h - c_f q_f\right] \frac{1}{2} d\theta - c_k k. \tag{3}$$

The integrand represents the firm's short-term profit once k has been chosen. The probability that a state θ occurs is $1/2$ dθ, θ being uniformly distributed over $[-1, 1]$. In each state θ, the firm selects q_h and q_f to maximize its short-term profit $pq - c_h q_h - c_f q_f$ with $q = q_h + q_f$ and subject to $q_h \leq k$ and $q_f \geq 0$. Whether the constraints are binding or not depend on the demand state. Since $c_f > c_h$ imports can only occur if the capacity is fully used.

Define two states θ^- and θ^+ such that: at θ^- (resp. θ^+) the production is equal to capacity and the marginal revenue at this production level is equal to the home variable cost (resp. the import price). These states respectively satisfy:

$$p(k, \theta^-) + \frac{\partial p}{\partial q}(q = k, \theta^-)k = c_h \tag{4}$$

$$p(k, \theta^+) + \frac{\partial p}{\partial q}(q = k, \theta^+)k = c_f. \tag{5}$$

These equations can be solved to get the expressions for θ^- and θ^+ as a function of k. These two states can be used to characterize three situations that can occur in the short-term, depending on the level of the demand. In low demand states, $-1 \leq \theta \leq \theta^-$, the firm has excess capacity and produces the monopoly unconstrained quantity ($q_h = (a + \lambda\theta - c_h)/2b$) without importing ($q_f = 0$). For intermediate levels of the demand, $\theta^- \leq \theta \leq \theta^+$, the firm produces at full capacity ($q_h = k$) and does not import ($q_f = 0$). Finally, when demand is large, $\theta^+ \leq \theta \leq 1$, the firm produces at full capacity and imports. The overall quantity produced is then determined by the cost of imports ($q = (a + \lambda\theta - c_f)/2b$). If demand variability is sufficiently large all three situations arise in equilibrium (i.e. $\theta^- > -1$ and $\theta^+ < 1$). The capacity constraint (i.e. $q_h \leq k$) is active only in the latter two situations.

In the long term, the firm chooses k to maximize its profit (3). The effect of the capacity on the short-term profit depends on the demand state. The long-term profit given by equation (3) may be rewritten as the sum of three integrals which corresponds to the three situations which may occur:

$$\begin{aligned}\pi(k) = &\int_{-1}^{\theta^-} [p(q, \theta) - c_h] q \frac{1}{2} d\theta + \int_{\theta^-}^{\theta^+} [p(k, \theta) - c_h)] k \frac{1}{2} d\theta \\ &+ \int_{\theta^+}^{1} [(p(q, \theta) - c_f)\, q + (c_f - c_h)k] \, \frac{1}{2} d\theta - c_k k\end{aligned} \tag{6}$$

The firm equalizes the expected short term marginal profit with the marginal cost of a capacity. The derivative of the first integrand is null since it does not depend on the capacity. The derivative of the second integral is constituted of the difference between the marginal revenue and the variable cost obtained when the capacity sets the price in intermediate demand situations. The derivative of the third term is the integral of $c_f - c_h$ which is precisely the short term cost reduction of substituting home production to imports when demand is large and the firm imports. Consequently, the optimal capacity satisfies the following first order condition:

$$c_k = \int_{-1}^{1} [p(q,\theta) + \frac{\partial p}{\partial q}(q,\theta)q - c_h]\frac{1}{2}d\theta \tag{7}$$

$$= \int_{-1}^{\theta^-} 0\frac{1}{2}d\theta + \int_{\theta^-}^{\theta^+} \left(p + \frac{\partial p}{\partial q}k - c_h\right)\frac{1}{2}d\theta + \int_{\theta^+}^{1}(c_f - c_h)\frac{1}{2}d\theta. \tag{8}$$

From this equation one gets the equilibrium capacity (1) and the equilibrium value of the threshold states (2). The equilibrium capacity of the oligopoly is proportional to the monopoly capacity by a factor $2n/(n+1)$. This feature does not depend on uncertainty and arise in a standard Cournot game with linear demand and cost. The absence of strategic effects explain that the introduction of irreversible investment and uncertainty does not modify this relationship. The total equilibrium production in low (resp. high) demand states corresponds to the unconstrained Cournot equilibrium with marginal cost c_h (resp. c_f). In intermediated situations, the capacity constraint of each firm is binding.

4 Results

This section identifies the impact of a unilateral CO_2 emissions tax in the home country on: the home investment, the leakage rate and the pass-through rate. In our framework a CO_2 emissions tax amounts to an increase in the home variable cost c_h. We obtain analytical results and provide a numerical illustration of each point. The illustration is useful to understand the underlying rationale and it gives an order of magnitude of the effects. The data used for the illustration is a very rough calibration of the cement sector (A).

4.1 Home capacity

Proposition 1

- *The optimal capacity decreases with respect to the CO_2 price,*

$$\frac{\partial k^*}{\partial c_h} < 0. \tag{9}$$

- *The larger the demand variability λ the larger the decrease:*

$$\frac{\partial^2 k^*}{\partial c_h \partial \lambda} < 0. \tag{10}$$

The proof is in C.1.

The first part of Proposition 1 states the standard result that a cost increase leads to a decrease in output, thus in capacity. The second result is the important one. It states that this decrease is amplified by the level of demand variability. It can be interpreted as follows. At all times, the equilibrium capacity is such that the expected marginal revenue is equal to the complete cost $c_h + c_k$ (rewriting equation 7). The reduction of the capacity ensures that this relation holds when the variable cost increases. When demand variability increases the capacity sets the price less frequently (Lemma 1 gives that the intermediate situation in which $\theta^- \leq \theta \leq \theta^+$ occurs less frequently). Therefore, a larger adjustment of the capacity is necessary to maintain the equilibrium relationship between the marginal revenue and the long-term cost.

A model that does not account for demand uncertainty will underestimate the effect of the CO_2 regulation on investment, and the larger the variability is the larger the underestimation will be.

Numerical illustration

In our illustration the data correspond to c_k=15€/t, c_h=25€/t, c_f=75€/t, $n = 6$. The emission rate is .65 tCO_2 per ton. The sensitivity analysis is made with respect to demand variability and the CO_2 price. In the graphs, for readability, we have picked the point at which demand variability is set at 15% and the CO_2 price is set at 40€/t (the variable cost increases by Δc_h= 25€/t).

Figure 1 and Figure 2(a) compare the decline of capacity as a function of the CO_2 price in a model with uncertainty (at 15%) and without uncertainty, respectively in percentage and in absolute values. Figure 2(b) compares the impact of demand variability on the absolute capacities for two values of the CO_2 price (0€/t and 40€/t). While the capacity increases with demand variability with a CO_2 price at 0€/t, it is decreasing for 40€/t.

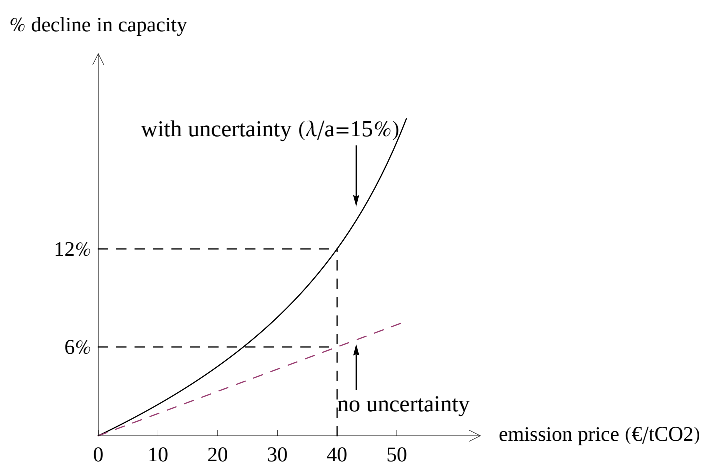
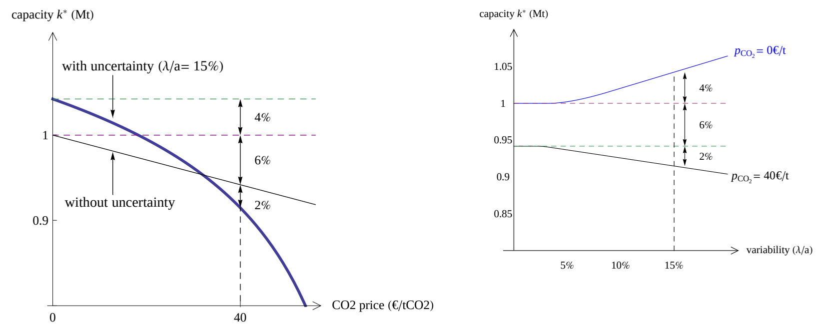


Figure 1: Percent decline in capacity with respect to the CO_2 price, with and without demand variations.



(a) The effect of the CO_2 price

(b) The effect of the demand variability

Figure 2: Individual capacity as a function of the CO_2 price (a) and demand variability (b).

4.2 Leakage

The leakage rate is the ratio between the rise of foreign emissions associated to imports and the decrease of home emissions. For simplicity we assume that foreign production and home production have the same emission rate. We shall consider both the short and long term leakage rates. In the short term the capacity is fixed at $k_n^*(\lambda, c_h)$. In the long term the capacity has been adapted to the carbon policy to become $k_n^*(\lambda, c_h + \Delta c_h)$ in which Δc_h represents the increase in variable cost induced by the CO_2 price.

Denote $q_h(k, c_h, \theta)$ and $q_f(k, c_h, \theta)$ the short term production (respectively home production and imports) of an oligopoly of n firms in which each firm has a capacity k/n. The expressions of these quantities are given by (21) in B.

The short term leakage rate is:

$$L_{ST} = \frac{\mathbb{E}\left[q_f(k_n^*(c_h), c_h + \Delta c_h, n, \theta) - q_f(k_n^*(c_h), c_h, n, \theta)\right]}{\mathbb{E}\left[q_h(k_n^*(c_h), c_h, n, \theta) - q_h(k_n^*(c_h), c_h + \Delta c_h, n, \theta)\right]}. \tag{11}$$

And the long term leakage rate is:

$$L_{LT} = \frac{\mathbb{E}\left[q_f(k_n^*(c_h + \Delta c_h), c_h + \Delta c_h, n, \theta) - q_f(k_n^*(c_h), c_h, n, \theta)\right]}{\mathbb{E}\left[q_h(k_n^*(c_h), c_h, n, \theta) - q_h(k_n^*(c_h + \Delta c_h), c_h + \Delta c_h, n, \theta)\right]}. \tag{12}$$

Proposition 2

- *The short term leakage rate is null.*
- *The long term leakage rate is increasing with respect to the level of demand variability.*

The proof is in C.2. From Lemma 1 we see that when imports occur, the total production does not depend on c_h and that imports depend on k. In the short term the capacity remains unchanged, the leakage rate is null.

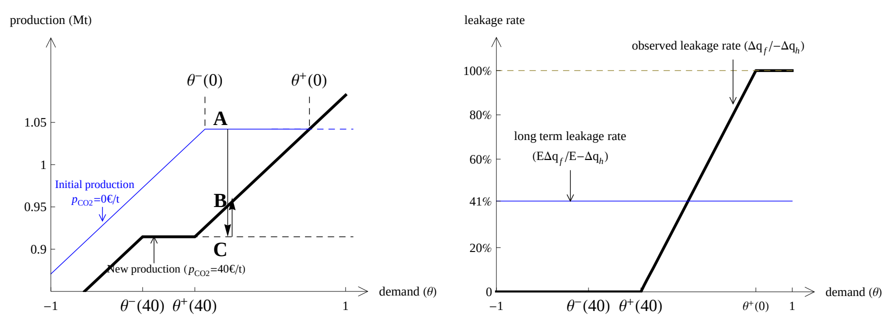
Consider now the long term leakage rate. To facilitate the interpretation of the result it is convenient to define the *observed* long term leakage rate, i.e. conditional on θ. It is given by (12) without the expectation operator. In the long-term there is leakage because of the reduction of capacity (Proposition 1). In high demand states, there are already imports with a CO_2 price at 0€/t, a higher CO_2 price will induce an increase of imports precisely equals to the decrease of capacity, the observed leakage rate is 100%. In other demand states the observed leakage rate will be between 0% and 100%. The higher the demand variability the higher the probabilities of the high demand states (cf. Lemma 1), the higher the (expected) long term leakage rate.

Numerical illustration

We first consider the case in which the demand variability and the CO_2 price are fixed (respectively at 15% and 40€/t CO_2). We show how the CO_2 price induces an observed long term leakage rate due to the change in capacity. Then we calculate the long term leakage rate for a large range of both demand variability and CO_2 prices.

Figure 3(a) depicts how the total production is affected when the CO_2 price goes up from 0 to 40€/t CO_2. The respective values of θ^- and θ^+ are reported. The points A, B, C illustrates a situation in which θ is in between $\theta^+(40)$ and $\theta^+(0)$. The total production decreases from A to B. There were no imports, now imports corresponds to the segment BC. The observed leakage rate is BC/AC.

Figure 3(b) gives the evolution of the observed long term leakage rate as a function of θ. For $\theta < \theta^+(40)$ it is 0. For $\theta^+(0) < \theta$ it is 100%. It increases linearly in the interval. The long term leakage rate (defined by 12) is also depicted.



(a) Production (b) Leakage rate

Figure 3: Production and the long term leakage rates.

The results of our sensitivity analysis are given in Table 2. The leakage rate is increasing with respect to the demand variability (proposition 2) and as function of the CO_2 price (which is a direct consequence of Proposition 1). Recall that, without demand uncertainty, there would not be any leakage in our model. The impact of uncertainty is significant. Even for a small price of 5€/t there is a non negligible leakage if the variability of the demand is of 15%. As could seen a CO_2 price of 5€/t with a demand variability of 20% gives a leakage similar than a CO_2 price of 20€/t and a variability of 15% .

		CO_2 price (€/t)					
		5	10	20	30	40	50
Demand Variability λ/a	5%	0 %	0%	0%	2%	10%	21%
	10%	5%	8%	13%	20%	29%	42%
	15%	16%	18%	24%	31%	41%	54%
	20%	23%	26%	32%	39%	49%	62%
	25%	29%	32%	38%	46%	55%	67%
	30%	34%	37%	43%	51%	60%	71%

Table 1: The long term leakage rate

4.3 Pass-through

The impact of the carbon price on the output price is measured by the pass through rate. This is the ratio between the output price change and the cost change. The short term pass through rate is:

$$PT_{ST} = \frac{\mathbb{E}\left[p\left(q\left(k_n^*\left(c_h\right), c_h + \Delta c_h, n, \theta\right), \theta\right) - p\left(q\left(k_n^*\left(c_h\right), c_h, n, \theta\right), \theta\right)\right]}{\Delta c_h} \tag{13}$$

and the long term one:

$$PT_{LT} = \frac{\mathbb{E}\left[p\left(q(k_n^*(c_h + \Delta c_h), c_h + \Delta c_h, n, \theta), \theta\right) - p\left(q(k_n^*(c_h), c_h, n, \theta), \theta\right)\right]}{\Delta c_h}. \tag{14}$$

Without uncertainty, the model corresponds to a standard Cournot oligopoly with linear demand and constant marginal cost, there are no imports and production equals capacity. In this case—to be referred as the *standard Cournot model*— the pass through rate is easily determined to be $n/(n+1)$.

Proposition 3

- *The long term pass through rate is equal to the one obtained in the standard Cournot model (it is $n/(n+1)$).*
- *The short term pass through rate is smaller than the long-term pass-through rate and increasing with respect to demand variability.*

The proof is in C.3. The long term pass through rate is independent of demand variability and therefore similar to the one obtained in the standard Cournot game. In the short term, the pass through is lower than in the long term one because the capacity is still at the pre-regulation level. The short term pass through rate increases with uncertainty because when λ increases, there are more states in which the firm has excess capacity and the variable cost sets the price (cf. Lemma 1).

We define both the long term and short term *observed* pass through rates for each value of θ. The expressions of these rates correspond to (13) and (14) without the expectation operator.[6]

While the first part of Proposition 3 would incline to minimize the role of uncertainty, the second part has empirical bearing. Moreover, Proposition 3 does not say the full story. As will be shown in the illustration, the observed long term pass through rates may significantly vary and under some situations be much higher than 100%!

Numerical Illustration

Again we first consider the case in which the demand variability and the CO_2 price are fixed (respectively at 15% and 40€/t CO_2) and secondly we calculate the short term pass through rate for a large range of both demand variability and CO_2 prices.

The output price and the observed pass through rates, both short term and long term, are depicted in Figure 4. Three zones emerge depending on the value of θ with respect to $\theta^-(40)$ and $\theta^+(0)$.

Firstly, for $\theta < \theta^-(40)$, capacity is not a constraint. The effect of the CO_2 price on the observed short and long term rates is similar, the pass through in these states is $n/(n+1)$ as in a standard Cournot model. Secondly, for $\theta > \theta^+(0)$, the price is set by the import cost and the pass through is null. In both cases there is no difference between short term and long term.

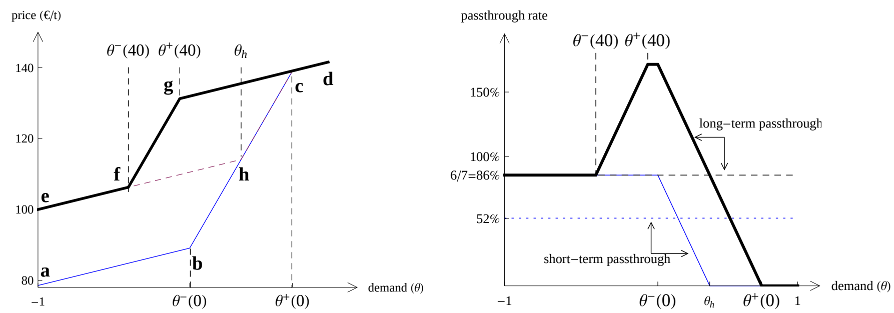
What happens in the median zone can be inferred from the graphs in Figure 4. The prices depicted in Figure 4(a) correspond to:

- **abcd** for $p_{CO2} = 0€/t$,
- **ehcd** ($p_{CO2} = 40€/t$) in the short term,
- **efgcd** ($p_{CO2} = 40€/t$) in the long term.

The pass through rates are depicted in Figure 4(b). The short term pass through rate is 52% and the long term one is 86%=n/(n+1)=6/7. The observed pass through rates in each demand state are also depicted. The observed short term pass through rate remains at 6/7 until $\theta^-(0)$ and then progressively decreases to zero at θ_h ($\theta_h = 0.4$ in the numerical illustration) and then remains at zero.

[6] Contrary to the leakage rate the short term (resp. long term) pass through rate is the expectation of the observed short term (resp. long term) pass through rate because the denominator (the change of the CO_2 price) is constant across demand states.

The observed long term pass through rate increases from 6/7 for $\theta^-(40) < \theta < \theta^+(40)$. It remains constant for $\theta^+(40) < \theta < \theta^-(0)$. It decreases to zero for $\theta^-(0) < \theta < \theta^+(0)$. The peak can be computed to be at 171%, which is well above 100%! It occurs because the adapted capacity creates a constraint while there would be none if the CO_2 price were zero. These numerical results emphasize that demand variations may have a major impact on the observed pass through rates.



(a) Price (b) Passthrough rate

Figure 4: Changes in output prices and the passthrough rates in each demand state (θ).

Our sensitivity analysis of the short term pass through rate with respect to the CO_2 price and demand variability is reported in Table 3. It is slightly increasing in both dimensions, from 20% to 57% and remains much lower than the one in the standard Cournot model (that is $6/7 = 86\%$).

Without uncertainty the short-term pass through would be null, the price would be solely determined by the capacity. However, even for relatively small variability and CO_2 price, there is a positive pass-through rate, this is so because the capacity constraint is relaxed in low demand state as the CO_2 price is implemented, and in these demand states the output price is increased.

		CO_2 price					
		5	10	20	30	40	50
Demand variability λ/a	5%	20%	23%	29%	34%	40%	46%
	10%	39%	40%	43%	46%	49%	51%
	15%	46%	47%	49%	51%	52%	54%
	20%	49%	50%	51%	53%	54%	56%
	25%	51%	52%	53%	54%	55%	57%
	30%	53%	53%	54%	55%	56%	57%

Table 2: Short term pass through rate (13).

5 Conclusion

The channel of carbon leakage explored in this paper had not been formally identified so far. While our results have been derived through a simple model we believe that they could be generalized and that they have some important policy implications.

A complete model would consider a set of N markets linked by transport costs with a subset of them being regulated. Firms would be multinationals choosing capacity in several markets and in the short-term each firm would decide how much to produce and transport in each market. Independent traders and pure domestic firms may also be introduced. Demand in the different markets may be more or less correlated to reflect the existence of regional and international business cycles. Such a model would be helpful to understand the effect of the environmental regulation not only on the trade patterns between regulated and unregulated countries but also long term relocation trends (e.g. between E.U. countries). One should also allow for more general dynamics based for instance on a Markov framework allowing for endogenous market structures, along the line introduced in Ryan (2012).

Our qualitative results on short term and long term effects are worth putting in a policy perspective. Firstly they provide a conceptual framework to interpret ex post analysis of leakage. Ellerman et al. (2010) attribute the absence of impacts of the first two phases of the EU-ETS to the idea that these impacts can only be observed in the long term. Branger et al. (2013) show that non EU imports (2000-2012) are better explained by the recent peak of economic activity in the EU than by the EU CO_2 prices. Both papers conclude that there has been no significant leakage. Our model is consistent with these observations and may provide some basis for disentangling short term and long term effects in empirical studies. Along the same lines it may be interesting to introduce demand uncertainty in the counter factual analysis carried on in Fowlie et al.

(2012). In their model, leakage occurs because of the existence of a competitive fringe. We may expect that the introduction of demand uncertainty would amplify leakage. Such an extension may be especially relevant for two reasons: the US construction activity is quite cyclical and domestic firms play a significant role in US imports through their control of a large fraction of import terminals, two factors which fit well with our model.

Secondly, our results may also be relevant for the analysis of remedies to leakage, taking into account the feed back of various schemes on investment policies. The design of the EU-ETS mechanism for 2013-2020 ((European Commission, 2011) was made in 2007 and completely ignored the economic crisis that occurred later years. In Meunier et al. (2012) we show that, when demand variations are sufficiently large, a combination of capacity and output based free allocation would be optimal. The multiplication of ETS at the regional level, the increasing concern for regional trade flows and the prevalence of economic cycles, make such analysis more and more relevant for all capital intensive exposed sectors.

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Appendix

A The numerical illustration

The cement industry provides a natural context to illustrate our results: the world cement market consists of a set of regional markets with limited interactions and subject to cyclical activity, the cement prices are notoriously very different from one region to the other one, the cross regional trade flows are low with respect to the overall production level, the large multinational firms indirectly control a large fraction of these flows.[7]

The data corresponding to the numerical illustration is given in Table 1. This data is illustrative of the EU cement industry and originates from Ponssard and Walker (2008). They would be representative of coastal regions such as the East or West coast in the US, Italy or Spain in the EU. The demand function is calibrated such that at the Cournot equilibrium with 6 firms without uncertainty, each firm produces 1 Mt, the market price is 100€/t and the price elasticity at the equilibrium is -0.27.

The demand fluctuations captured through the parameter λ/a corresponds to the average demand fluctuations of a European country over the last 20 years. The variable costs in € per ton of cement are: for investment $c_k = 15$ (annualized over a 40 years life duration for a plant), for home production $c_h = 25$, for import $c_f = 75$ (involving sea transport, terminal cost and further inland transportation by road; it is suggestive of an inland region). We consider the implementation of a CO_2 price of 40€/tCO_2 and an emission rate of .65 tCO_2 per ton of cement, so $\Delta c_h = 25$.

Cost parameters (€/t)	
c_k	15
c_h	25
c_f	75
Δc_h	40€/t$CO_2 \times$ 0.65 $=$ 25

Demand Parameters	
a (€/t)	470
b (€/t^2)	61.7
λ/a	15%

Table 3: Parameters for the illustration

[7] These facts are well documented in analysts' reports. Note in particular that "2.3% of the global cement was traded in 2011 and around 50% was undertaken by the top five global cement companies" source Building Materials, Jefferies International Equity Research, August 2012, page 153 https://javatar.bluematrix.com/docs/pdf/dc9e917a-86d9-4e29-82cd-b12a55f4741a.pdf.

B Proof of Lemma 1

Expression of the thresholds

We first express the thresholds θ^- and θ^+ in the short-term, with a fixed capacity k.

If demand varies sufficiently (large λ) at the low (resp. high) threshold state θ^- (resp. θ^+) the unconstrained monopoly production with marginal cost c_h (resp. c_f) is precisely equal to the capacity. For small λ the thresholds are -1 or 1 respectively. This gives:

$$\theta^- = \max\left\{\left(2bk - a + c_h\right)/\lambda, -1\right\} \tag{15}$$

$$\theta^+ = \min\left\{\left(2bk - a + c_f\right)/\lambda, 1\right\} \tag{16}$$

The monopoly capacity

The monopoly long term profit is a strictly concave function of $k \in [0, (a + \lambda - c_h)/2b$. There is a unique profit maximizing capacity k^* that solves the first order condition (8).

Four situations can arise whether at k_1^*: $\theta^- = -1$ or not and $\theta^+ = 1$ or not. The level of demand variability and the cost parameters determine in which situation we are. We limit ourselves to the case in which the demand variability is sufficiently large so that $\theta^- > -1$ and $\theta^+ < 1$ (the expressions in the other situations could be obtained by request to the authors).

In that case, $a + \lambda\theta^- - 2bk_1^* = c_h$, and $a + \lambda\theta^+ - 2bk_1^* = c_f$. Therefore, from equation (8) we have:

$$\begin{aligned}
2c_k &= \int_{\theta^-}^{\theta^+} [(a - 2bk) + \lambda\theta - c_h] d\theta + (1 - \theta^+)(c_f - c_h) \\
&= \int_{\theta^-}^{\theta^+} \lambda(\theta - \theta^-) d\theta + (1 - \theta^+)(c_f - c_h) \\
&= \lambda(\theta^+ - \theta^-)^2/2 + (1 - \theta^+)(c_f - c_h) \\
&= (c_f - c_h)^2/2\lambda + (1 - \theta^+)(c_f - c_h) \qquad \text{for } \theta^+ - \theta^- = \frac{c_f - c_h}{\lambda}
\end{aligned}$$

Then, the two thresholds are given by the equations (2). Replacing θ^+ in (2) by its expression (16) gives:

$$k_1^* = \left[a - \left(c_f + c_h\right)/2 + \lambda\left(1 - 2c_k/(c_f - c_h)\right)\right]/2b. \tag{17}$$

The thresholds are indeed respectively higher than -1 and lower than 1 if and only if λ is sufficiently large:

$$\begin{aligned}
\left(2bk_1^* - a + c_h\right)/\lambda > -1 \quad &\Leftrightarrow \quad \lambda > \left(c_f - c_h\right)^2/4(c_f - c_h - c_k), \\
\left(2bk_1^* - a + c_f\right)/\lambda < 1 \quad &\Leftrightarrow \quad \lambda > (c_f - c_h)^2/4c_k.
\end{aligned}$$

The oligopoly capacity

A sketch of the proof is provided, a more detailed one can be obtained by request to the authors.

Assume that there are n firms. Each firm simultaneously chooses its capacity and a production plan. At an equilibrium: on the short term, in each demand state firms play a constrained Cournot game with two technologies available, and, in the long term, each firm capacity is a solution of a first order equation that equalizes the capacity cost c_k with expected short term marginal profit. Any equilibrium is symmetric because the expected marginal short term profit of two firms is equal if and only if their capacities are equal. Then the only possible equilibrium is symmetric and the aggregate equilibrium capacity k_n^* is such that the individual expected marginal short-term profit is equal to the capacity cost, k_n^* is the unique solution of the equation:

$$\int_{\theta^-(n,k)}^{\theta^+(n,k)} \left(a - c_h + \lambda\theta - \frac{n+1}{n}bk\right) d\theta + \int_{\theta^+(n,k)}^{1} (c_f - c_h)d\theta - 2c_k = 0 \quad (18)$$

where $\theta^-(n,k)$ and $\theta^+(n,k)$ are :

$$\begin{aligned} \theta^- &= \max\left\{((n+1)bk/n - a + c_h)/\lambda, -1\right\}, && (19)\\ \theta^+ &= \min\left\{((n+1)bk/n - a + c_f)/\lambda, +1\right\}, && (20) \end{aligned}$$

and aggregate equilibrium productions $q_h(k, c_h, n, \theta)$ and $q_f(k, c_h, n, \theta)$ are the constrained Cournot one:

$$\left.\begin{array}{rcl} 0 \le \theta \le \theta^- & : & q_h = n(a + \lambda\theta - c_h)/b(n+1) \text{ and } q_f = 0 \\ \theta^- \le \theta \le \theta^+ & : & q_h = k \text{ and } q_f = 0 \\ \theta^+ \le \theta \le 1 & : & q_h = k \text{ and } q_f = n(a + \lambda\theta - c_f)/b(n+1) - k \end{array}\right\} \quad (21)$$

By injecting expressions (19) and (20) of θ^- and θ^+ into the first order condition (18) it appears that the thresholds are solution of an equation independent of n. Hence, equilibrium values of threshold states are independent of n and given by (2), and the oligopoly capacity is

$$k_n^* = \frac{n}{n+1}\frac{1}{b}\left[a - \frac{c_h + c_f}{2} + \lambda\left(1 - 2\frac{c_k}{c_f - c_h}\right)\right].$$

And finally, the solution of equation (18) and the corresponding productions (21) are equilibrium strategies because individual profit of each firm is concave and first order conditions are satisfied.

C Results

C.1 Proof of Proposition 1

We use the expression established in Lemma 1. The derivatives of k_n^* in equation (1) are

$$\frac{\partial k_n^*}{\partial c_h} = \frac{-1}{b}\frac{n}{n+1}\left[\frac{1}{2} + \frac{2\lambda c_k}{(c_f - c_h)^2}\right] < 0; \; \frac{\partial k_n^*}{\partial \lambda \partial c_h} = \frac{n}{n+1}\frac{-2c_k}{b(c_f - c_h)^2} < 0.$$

C.2 Proof of Proposition 2

The expected quantity produced domestically is

$$Q_h(k, c_h, \lambda) \underset{def}{=} \mathbb{E}q_h = \int_{-1}^{\theta^-} \frac{n}{n+1}\frac{1}{b}(a + \lambda\theta - c_h)\frac{1}{2}d\theta + \int_{\theta^-}^{1} k\frac{1}{2}d\theta \tag{22}$$

and the expected quantity imported:

$$Q_f(k, c_h, \lambda) \underset{def}{=} \mathbb{E}q_f = \int_{\theta^+}^{1} \left[\frac{n}{n+1}\frac{1}{b}(a + \lambda\theta - c_f) - k\right]\frac{1}{2}d\theta \tag{23}$$

The short-term leakage rate is null because Q_f does not depend on c_h, so the numerator of (11) is null.

The long term leakage rate (12) is independent of n because both the numerator and the denominator are proportional to $n/(n+1)$ (remember that θ^- and θ^+ are independent of n at equilibrium and that k_n^* is proportional to $n/(n+1)$).

We write the changes of expected production:

$$\Delta Q_i = Q_i(k_n^*(c_h + \Delta c_h), c_h + \Delta c_h, \lambda) - Q_i(k_n^*(c_h), c_h, \lambda), \text{ for } i = f, h.$$

Thus, the leakage rate (12) is $L_{LT} = \Delta Q_f/(-\Delta Q_h)$. To determine the effect of λ on this rate, we proceed in several steps.

We first show that ΔQ_f is decreasing with respect to λ. From equations (23),

$$\frac{dQ_f}{dc_h} = \frac{\partial Q_f}{\partial c_h} + \frac{\partial Q_f}{\partial k}\frac{\partial k_n^*}{\partial c_h} = 0.5(1 - \theta^+)(-\frac{\partial k_n^*}{\partial c_h}) \tag{24}$$

Then, from Proposition 1 the derivative of k_n^* is decreasing w.r.t. λ, and from the equations (2) the equilibrium threshold θ^+ is decreasing w.r.t. to λ. Therefore, dQ_f/dc_h is increasing w.r.t. to λ and so is ΔQ_f.

Second, we show that the expected quantity consumed, $Q_h + Q_f$, is independent of λ. At equilibrium, the equation (18) is satisfied, and, for $\theta < \theta^-$ $c_h = a + \lambda\theta - b(n+1)q_h/n$ and for $\theta > \theta^+$, $c_f = a + \lambda\theta - b(n+1)(q_f + k)/n$, therefore:

$$\int_{-1}^{\theta^-} \left[(a + \lambda\theta) - b\frac{n+1}{n}q_h - c_h\right]\frac{1}{2}d\theta + \int_{\theta^-}^{\theta^+} \left[(a + \lambda\theta) - b\frac{n+1}{n}k - c_h\right]\frac{1}{2}d\theta$$
$$+ \int_{\theta^+}^{1} \left[(a + \lambda\theta) - b\frac{n+1}{n}(q_f + k) - c_h\right]\frac{1}{2}d\theta = c_k$$

Then, injecting the expressions (22) and (23) of expected home and foreign production, these quantities satisfy the following equation at equilibrium:

$$Q_f(k_n^*, c_h, \lambda) + Q_h(k_n^*, c_h, \lambda) = \frac{1}{b}\frac{n}{n+1}[a - (c_h + c_k)]. \tag{25}$$

Note that it corresponds to the equality of the expected marginal revenue with the long-term cost (equation 7 in the monopoly case).

Finally, from equation (25) we obtain

$$\Delta Q_f + \Delta Q_h = -\frac{nb}{n+1}\Delta c_h$$

and dividing both sides by ΔQ_f we get:

$$\frac{1}{L_{LT}} = 1 + \frac{nb}{n+1}\frac{\Delta c_h}{\Delta Q_f}.$$

L_{LT} is increasing with respect to λ because ΔQ_f is.

C.3 Proof of Proposition 3

We first proove the result relative to the long-term pass-through rate. We consider the derivative of the expected price denoted $\mathbb{E}p$ with respect to c_h. The total derivative is composed of two components a direct one and an indirect one:

$$\frac{d\mathbb{E}p}{dc_h} = \frac{\partial \mathbb{E}p}{\partial c_h} + \frac{\partial \mathbb{E}p}{\partial k}\frac{\partial k^*}{\partial c_h} \tag{26}$$

With the expression (21) for home production, the first term is $\partial\mathbb{E}p/\partial c_h = 0.5\,(\theta^- + 1)\,n/(n+1)$. The second term is related to the change of capacity. A marginal change of capacity increases expected price of $\partial\mathbb{E}p/\partial k = (\theta^+ - \theta^-)\,b/2$. From the first order condition (18) $\partial k_n^*/\partial c_h = n/(b(n+1))(1 - \theta^-)/(\theta^+ - \theta^-)$.

$$\frac{d\mathbb{E}p}{dc_h} = 0.5\left[\left(\theta^- + 1\right)\frac{n}{n+1} + \left(\theta^+ - \theta^-\right)b\frac{(1-\theta^-)}{(\theta^+ - \theta^-)}\frac{n}{b(n+1)}\right] = \frac{n}{n+1}$$

Therefore, the long-term pass-through rate is

$$PT_{LT} = \frac{1}{\Delta c_h}\int_0^{\Delta c_h}\frac{d\mathbb{E}p}{dc_h}dc_h = \frac{n}{n+1} \tag{27}$$

Concerning, the short-term pass-through rate. It could be written

$$PT_{ST} = \frac{1}{\Delta c_h}\int_0^{\Delta c_h}\frac{\partial\mathbb{E}p}{\partial c_h}dc_h. \tag{28}$$

- It is smaller than the long-term one because the second term of (26) is positive (the capacity is decreasing w.r.t. the variable cost);
- The derivative of the price $\partial\mathbb{E}p/\partial c_h$ is $0.5(1+\theta^-)n/(n+1)$, and θ^- is increasing with respect to λ (cf equation (15)) so $\partial\mathbb{E}p/\partial c_h$ is increasing w.r.t. λ and so is the short-term pass-through rate.